FUEL COMPOSITION EFFECTS ON NATURAL GAS VEHICLE EMISSIONS

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ABSTRACT
Under a contract from DOE's National Renewable Energy Laboratory (NREL) and support from Brooklyn Union Gas Company (BUG), Northern Illinois Gas Co., the Institute of Gas Technology (IGT) evaluated four state-of-the-art, electronic, closed-loop natural gas vehicle (NGV) conversion systems. The systems included an Impco electronic closed-loop system, Mogas electronic closed-loop system, Stewart & Stevenson's GFI system, and an Automotive Natural Gas Inc. (ANGI) Level I electronic closed-loop conversion system. Conversion system evaluation included emission testing per 40 CFR Part 86, and driveability. All testing was performed with a 1993 Chevy Lumina equipped with a 3.1 L MPFI V6 engine. Each system was emission tested using three different certified compositions of natural gas, representing the 10th, mean and 90th percentile gas compositions distributed in the United States. Emission testing on indolene was performed prior to conversion kit testing to establish a base emission value. Indolene testing was also performed at the end of the project when the vehicle was converted to its OEM configuration to ensure that the vehicle's emissions were not altered during testing. The results of these tests will be presented.

INTRODUCTION
A number of conversion systems are commercially available to convert gasoline fueled vehicles to either dedicated or bi-fueled natural gas vehicles (NGVs). This paper presents the research results to date of four NGV conversion systems tested on the 1993 3.1L MPFI Chevrolet Lumina passenger car. This study included fuel emission testing based on the Federal Test Procedure (FTP) per 40 CFR Part 86 and fuel economy measurements using three different compositions of natural gas. Emission testing on indolene was performed prior to conversion system testing to establish gasoline base emission values. Any variations in emissions or fuel economy related to fuel quality will be better understood as a result of the FTP emission testing program. In addition to fuel quality, this investigation also evaluated conversion system performance, both in terms installation and driveability. All procedures required to convert the gasoline fueled vehicle to compressed natural gas (CNG) were fully documented including hardware installation, electronic hookups, and system calibration.

SPECIFICATION OF NATURAL GAS COMPOSITION
Natural gas is not pure methane or a homogeneous mixture, but varies in composition by location and seasonally. Variations occur between the originating fields and may be further modified due to processing prior to transmission. Additional mixing of different gases also occurs during pipeline transmission. As a result, natural gas does not describe a single type of fuel or a narrow range of characteristics, unlike gasoline or diesel fuel which is manufactured within certain specifications.

Fuel composition can affect vehicle emissions. The most recent work on natural gas composition was completed in 1991 by the American Gas Association Laboratories with the Institute of Gas Technology as a subcontractor, under Gas Research Institute funding.[1] The research focused on the mean average, minimum, maximum, 10th percentile, and 90th percentile gas fractions. However, information reported in the GRI sponsored study for the mean, 10th percentile, and 90th percentile values for each of the component gases allowed for only a pseudo-composition to be developed. For example, the 10 percentile value of methane could be combined with the 90th percentile values of the other constituents for a minimum-methane concentration natural gas. The rationale for this approach is that, when methane dominates the composition, the other gases would be expected to be at their lower values. However, this does not take into account that natural gas compositions are not manufactured but occur normally with certain relationships between each of the components. As a result, IGT concluded that a more detailed review was necessary to determine representative natural gas compositions.

Two primary factors that impact emissions and directly describe the general characteristics of natural gas include the concentration of methane and the Wobbe number. The methane concentration is a good measure because it is the dominant component in natural gas. The Wobbe number is a measure of the fuel energy flow rate through a fixed orifice under given inlet conditions. It is calculated as the ratio of the higher heating value divided by the square root of the specific gravity. Variations in Wobbe number of the gas will produce similar variations in the air-fuel ratio for gas metering systems used on vehicles. Variability of this parameter will most significantly affect engines equipped with open-loop controls, where the exhaust oxygen cannot be sensed and adjusted. In general, the Wobbe number is a good criteria for natural gas because it correlates well with the ability of an internal combustion engine to use a particular gas. It also takes into account many of the gas components because it is a bulk property.

The first step was to determine the minimum, maximum, mean average, median, 10th percentile, and 90th percentile values for the methane mole fraction, as shown in Table 1. This data represents over

6,000 gas samples taken from various locations throughout the continental U.S. It should be noted that the minimum value represents propane/air peakshaving gas. This gas is generated by many local utilities during severe periods of high demand which typically occur during the coldest periods of the year. During mild winters these plants may not even be used and during normal winters plants may only operate 1 to 2 days per year. The equivalent values for the Wobbe number are shown in Table 2.

TABLE 1. METHANE FRACTION ANALYSIS

Minimum:	55.8%
Maximum:	98.1%
Mean (avg):	93.0%
Std Deviation:	4.5%
Median:	94.9%
10th Percentile:	84.1%
90th Percentile:	96.3%

TABLE 2. WOBBE NUMBER ANALYSIS

Minimum:	1202.6
Maximum:	1418.7
Mean (avg):	1329.4
Std Deviation:	42.6
Median:	1347.0
10th Percentile:	1233.0
90th Percentile:	1358.5

Having identified the methane fraction and Wobbe number values to be used, the next step was to define a suitable method of calculating the mole fractions of each of the other components. Because of the inherent variability of an individual natural gas sample, it was unlikely that a representative composition could be formulated from just the few values that fit exactly on the selected Wobbe number values. To select a slightly wider, more representative range of natural gas compositions at a given value, the average of each of the components was calculated considering only those samples within 2 Wobbe number counts of the identified Wobbe number. These results are shown in Table 3 (values presented are mole %). The near equivalency between methane fraction and Wobbe number for the natural gas composition can be seen in comparing the resulting averages for each of the components in each of the desired ranges. For example, the methane and Wobbe number for the two 10th percentile compositions are fairly close, 83.84 mole % vs. 83.96 mole % and 1229.76 vs. 1232.97. This holds true for the other components. Although there is more variability within the mean and 90th percentile compositions, the differences are within the variations that may be seen throughout the year.

TABLE 3. COMPOSITION BASED ON WOBBE NUMBER

	10%-ile	Mean	90%-ile
METHANE	83.96	92.87	94.80
ETHANE	5.72	3.34	3.03
PROPANE	1.07	0.63	0.58
I-BUTANE	0.09	0.07	0.10
N-BUTANE	0.11	0.12	0.13
I-PENTANE	0.03	0.04	0.05
N-PENTANE	0.01	0.03	0.03
C6+	0.03	0.05	0.07
NITROGEN	6.05	2.07	0.56
CO_2	1.40	0.78	0.65
O_2	1.53	0.00	0.00
WOBBE	1232.97	1329.15	1358.61

Because fuel metering is a critical factor in all NGV conversion systems, both IGT and NREL agreed that the gas compositions based on the Wobbe number, as presented in Table 3, should be used for the test fuels. High pressure gas cylinders were then prepared for each of the three compositions and certified by IGT for use in this test program.

BASELINE EMISSION TEST

IGT leased a new 1993 Chevy Lumina 3.1 liter MPFI V6 (VIN# 2G1WN54T7P9146384) for the testing program. During December of 1992 and January of 1993 the vehicle was driven 5,000 mostly highway miles on gasoline to ensure proper engine break-in and catalyst aging. An inspection was performed on the Lumina at 4,803 to establish baseline parameters prior to emission testing and conversion.

FTP emission testing on indolene were initiated in March, 1993 per 40 CFR Part 86 on the Chevy Lumina. Two baseline indolene tests were performed with the dynamometer set for a 3,500 pound inertia and 6.0 ahp. The vehicle odometer read 6,410 miles. The test results are presented in Table 4. As can be seen from the test results, the vehicle passed the exhaust emissions and shed test. Weighted total hydrocarbon values were 0.23 and 0.27, carbon monoxide 2.74 and 2.84, nitrous oxides 0.48 and 0.49, carbon dioxide 489 and 491, respectively reported in grams per mile, with fuel economy for both tests at 18.0 mpg. The shed test results were 0.34 and 0.39 grams respectively.

CNG EMISSION TEST RESULTS

All systems were installed and setup according to the manufacturer's instruction. Following the installation, a test drive and dynamometer set-up were performed using a snap-on analyzer for ECM parameters. Power valve and idle adjustment were performed to minimize tailpipe emissions (through the converter) without sacrificing driveability. Following these adjustments, IGT conducted driveability tests following the CRC Report No. 577 "1990 CRC Driveability Workshop" recommendations published in October 1990.[2] All four systems passed the driveability tests with no faults and did not experience engine stalling or hesitation, nor any problems with starting.

TABLE 4. EXHAUST AND EVAPORATIVE INDOLENE EMISSIONS DATA

Test Fuel Indolene		
Test Date	3/12/93	3/15/93
Vehicle Odometer, miles	6410	6429
Exhaust Emission Results		
Cold Transient, grams		
THC (C_3H_8 calibration)	2.65	3.15
CH_4 (a)	0.22	0.26
NMHC (a)	2.40	2.85
CO	23.24	26.97
NO_x	4.25	3.95
CO_2	1741	1767
Fuel Economy, MPG	17.9	17.6
Cold Stabilized, grams		
THC (C_3H_8 calibration)	0.34	0.25
CH_4 (a)	0.12	0.12
NMHC (a)	0.20	0.11
CO	4.70	4.32
NO_x	1.14	1.21
CO_2	1992	2004
Fuel Economy, MPG	17.9	17.0
Hot Transient, grams		
THC (C_3H_8 calibration)	0.45	0.74
CH_4 (a)	0.13	0.14
NMHC (a)	0.29	0.57
CO	9.82	8.99
NO_x	1.02	1.22
CO_2	1533	1536
Fuel Economy, MPG	20.5	20.5
Weighted Total, grams / mile		
THC (C_3H_8 calibration)	0.23	0.27
CH_4 (a)	0.04	0.04
NMHC (a)	0.19	0.22
CO	2.74	2.84
NO_x	0.48	0.49
CO_2	489	491
Fuel Economy, MPG	18.0	18.0
Shed, grams		
Diurnal 0.12	0.20	
Hot Soak	0.22	0.19
Total 0.34	0.39	

All emission tests were performed at the AutoResearch Laboratories per 40 CFR Part 86. The dynamometer was set for a 3,500 pound inertia and 6.0 ahp. The preliminary test results for the MOGAS system as tested in April, 1993 are presented in Table 5 for the three different gas compositions. From the weighted total results, it became clear that the vehicle was set-up lean following Mogas's set-up instructions. IGT did not attempt to optimize the emission results during set-up. However, the results do indicate that NO_x emissions could be reduced running richer, and thereby increasing carbon monoxide emissions which are currently significantly below the limit. It should be noted that for the 10th percentile gas the system did not pass the 1993 EPA NOx limit of 1.0 gr./mile.

The preliminary test results for the Impco system as tested in May, 1993 are presented in Table 6. As was the case with the MOGAS system, the weighted total test results indicate that the vehicle was set-up lean following Impco's set-up instructions. IGT did not attempt to optimize the emission results during set-up. Again, the results indicate that NO_x emissions could be reduced running richer, and thereby increasing carbon monoxide emissions which are currently significantly below the limit. However, the system met all applicable 1993 EPA emission standards for the entire range of natural gas compositions tested.

The preliminary test results for the GFI system as tested in July, 1993 are presented in Table 7. From weighted total results for the mean gas composition, it became clear that the vehicle was set-up rich by the GFI provided software. The carbon monoxide average (4.04 g/mile) was above the 3.4 g./mile EPA limit. However, the results do indicate that CO emissions could be reduced running leaner, and thereby increasing NOx emissions which are currently significantly below the limit. Since the software version supplied by GFI is specific to the 1993 Lumina tested, software changes may be required to "re-calibrate" the vehicle.

The weighted total results for the 90th and 10th percentile gas compositions further confirmed that the vehicle was set-up rich by the GFI provided set-up software. However, a closer analysis of the test results by IGT indicated that the 90th and the 10th percentile gas composition tests did not concur with the repeatability guidelines set forth in the publication "Statistical Design and Analysis Methods for the Auto/Oil Air Quality Research Program" as published by Painter and Rutherford in SAE paper 920319.[3] Of the tests reported, the HC, CO, and NO_X cold stabilized test pairs and the HC weighted total values from the 90th percentile gas composition did not meet this criteria. Likewise for the tests conducted on 10th percentile gas composition, the NO_X and HC cold transient test pairs and the HC, CO, and NO_X hot transient pairs also were above the limiting ratios. Further investigation indicated that an "air leak" in the testing equipment may have been a contributing cause to these differences.

As a result of this discrepancy noted above, a third test was performed for just the 90th and 10th percentile gas compositions to verify that the "air leak" was corrected and to provide further correlation of the test results. The data for these additional tests are summarized in Table 7 along with the previous test data. As can be seen, the 90th and 10th percentile "third" test data agree more closely to the "first" tests performed on each composition. However, based on the Auto/Oil reference sited above, IGT took the recommended approach of averaging the three tests for the average values reported for the 90th and 10th percentile gas composition tests.

Based on the average values for each of the gas compositions, the GFI system failed the CO emissions test based on the 1993 CO standard of 3.4 g/mi. However, two factors must be taken into consideration when assessing the GFI system. Both the related NOx emission values and the system setup requirements and system sophistication. Unlike the previous two systems tested, the GFI system requires information about the gas composition during vehicle setup and calibration. For this test IGT used the system default values and did not attempt to "dial in" the gas composition for each of the three gas compositions tested. Since the other two systems were not "tuned" on each composition, it was decided that this would give the GFI system an advantage. Second, and even more important, unlike the other systems, the GFI system incorporates a built in learning algorithm in the electronic controls which gradually adjusts the fuel/gas mixture in response to operating parameters such as exhaust oxygen sensor output relative to load. This learning adjustment occurs gradually during normal driving. However, due to the nature of the emission testing, the vehicle was not driven between tests to allow the system to adjust to the new fuel composition. Because of the cost of the certified test fuel, driving between tests was not deemed practical. Since the GFI system incorporates an adaptive learning electronic control system, given enough time on a given gas composition, this system may have passed all of the emission standards. The very low and consistent NOx levels of the GFI system also suggest that this system may have the capability of meeting 1994 standards, even on the 1993 test vehicle

The preliminary test results for the ANGI system as tested in October, 1993 are presented in Table 8. From weighted total results for the mean gas composition, the average levels of CO and NO_X emissions are well below the current EPA limits. The weighted totals for the 10th percentile composition indicate that the ANGI system failed the current NO_X standard of 1.0 g/mile. This indicates that the system produced very low emission levels with the mean composition gas, but the 10th percentile composition caused the system to run too lean.

The test results for the 90th percentile gas composition for the levels of CO did not concur with the repeatability guidelines set forth in the Auto/Oil reference. Again, based on Auto/Oil recommendations, a third test was performed. The results of the second and third tests were within recommended limits. Since there was a possibility of high background levels of CO during the first test and since the second and third test results were in close agreement, the first test was treated as an outlier and the average results were taken from tests 2 and 3. Thus, the weighted total test results for the 90th percentile were well within the EPA limits for CO and NO_X. This indicates that the ANGI system operates well on the mean and 90th percentile compositions which have a higher methane content, but the system fails current EPA limits on NO_X emission levels when operating with 10th percentile gas composition fuel.

CONCLUSIONS

As can be seen from these results, the Mogas system produced the lowest carbon monoxide test results followed by the Impco, ANGI and GFI systems. The GFI system actually failed the CO emissions test based on the 1993 CO standard of 3.4 g/mi. However, two factors must be taken into consideration when assessing the GFI system. Unlike the other 2 systems, the GFI system requires information about the gas composition during vehicle setup and calibration. For this test IGT used the system default values and did not attempt to "dial in" the gas composition for each of the three gas compositions tested. Since the other two systems were not "tuned" on each composition, it was decided that this would give the GFI system an advantage. Second, and even more important, unlike the other systems, the GFI system incorporates a built in learning algorithm in the electronic controls which gradually adjusts the fuel/gas mixture in response to operating parameters such as exhaust oxygen sensor output relative to load. This learning adjustment occurs gradually during normal driving. However, due to the nature of the emission testing, the vehicle was not driven between tests to allow the system to adjust to the new fuel composition. Because of the cost of the certified test fuel, driving between tests was not deemed practical.

TABLE 5. MOGAS SYSTEM EMISSIONS SUMMARY

Fuel Type Mean CNG		
Vehicle Odometer, miles	6821	6832
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.41	1.40
CH_4 (a)	1.40	1.42
NMHC (a)	0.16	0.11
CO	0.39	0.19
NO_x	0.85	0.90
CO_2	363	357
Fuel Economy, MPG	18.9	19.1
Fuel Type 90th Percentile CNG		
Vehicle Odometer, miles	6858	6869
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.28	1.37
CH_4 (a)	1.22	1.34
NMHC (a)	0.16	0.09
CO	0.59	0.28
NO_x	0.79	0.83
CO_2	351	355
Fuel Economy, MPG	19.2	19.0
Fuel Type 10th Percentile CNG		
Vehicle Odometer, miles	6898	6910
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.72	1.98
CH_4 (a)	1.66	2.00
NMHC (a)	0.17	0.18
CO	0.12	0.13
NO_x	1.03	1.01
CO_2	355	359
Fuel Economy, MPG	20.7	20.4

TABLE 6. IMPCO SYSTEM EMISSIONS SUMMARY

Mean CNG		
Vehicle Odometer, miles	7309	7320
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.01	1.03
CH_4 (a)	1.11	1.01
NMHC (a)	0.04	0.05
CO	0.80	0.54
NO_x	0.82	0.83
CO_2	379	376
Fuel Economy, MPG	18.1	18.2
Fuel Type 90th Percentile CNG		
Vehicle Odometer, miles	7280	7291
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.04	0.97
CH_4 (a)	1.03	1.10
NMHC (a)	0.05	0.04
CO	1.74	1.31
NO_x	0.57	0.63
CO_2	378	373
Fuel Economy, MPG	17.8	18.0
Fuel Type 10th Percentile CNG		
Vehicle Odometer, miles	7251	7262
Exhaust Emission Results		
Weighted Total, grams / mile		
THC (CH_4 calibration)	1.65	1.79
CH_4 (a)	1.63	1.82
NMHC (a)	0.14	0.14
CO	0.02	

TABLE 7. GFI SYSTEM EMISSIONS SUMMARY

Fuel Type Mean CNG			
Vehicle Odometer, miles	7620	7630	
Exhaust Emission Results			
Weighted Total, grams / mile			
THC (CH_4 calibration)	1.31	1.21	
CH_4 (a)	1.30	1.26	
NMHC (a)	0.08	0.07	
CO	4.16	3.92	
NO_x	0.18	0.22	
CO_2	389	394	
Fuel Economy, MPG	17.3	17.1	
Fuel Type 90th Percentile CNG			
Vehicle Odometer, miles	7650	7661	7854
Exhaust Emission Results			
Weighted Total, gr. / mile			
THC (CH_4 calibration)	1.27	0.77	1.18
CH_4 (a)	1.20	0.79	1.36
NMHC (a)	0.07	0.05	0.05
CO	4.27	2.56	4.05
NO_x	0.22	0.19	0.27
CO_2	373	378	382
Fuel Economy, MPG	17.8	17.7	17.4
Fuel Type 10th Percentile CNG			
Vehicle Odometer, miles	7691	7710	7873
Exhaust Emission Results			
Weighted Total, gr. / mile			
THC (CH_4 calibration)	1.05	1.04	1.00
CH_4 (a)	1.07	1.01	1.02
NMHC (a)	0.08	0.07	0.07
CO	3.40	3.16	3.36
NO_x	0.23	0.19	0.26
CO_2	395	377	386
Fuel Economy, MPG	18.5	19.4	18.9

TABLE 8. ANGI SYSTEM EMISSIONS SUMMARY

Fuel Type Mean CNG			
Vehicle Odometer, miles	8610	8621	
Exhaust Emission Results			
Weighted Total, grams / mile			
THC (CH_4 calibration)	0.52	0.50	
CH_4 (a)	0.49	0.52	
NMHC (a)	0.04	0.03	
CO	1.40	1.29	
NO_x	0.11	0.12	
CO_2	384	385	
Fuel Economy, MPG	17.9	17.8	
Fuel Type 90th Percentile CNG			
Vehicle Odometer, miles	8670	8681	8808
Exhaust Emission Results			
Weighted Total, g / mile			
THC (CH_4 calibration)	0.78	0.54	0.56
CH_4 (a)	0.82	0.53	0.58
NMHC (a)	0.04	0.03	0.05
CO	5.05	1.95	1.60
NO_x	0.09	0.18	0.10
CO_2	397	392	394
Fuel Economy, MPG	16.7	17.2	17.1
Fuel Type 10th Percentile CNG			
Vehicle Odometer, miles	8632	8651	
Exhaust Emission Results			
Weighted Total, g / mile			
THC (CH_4 calibration)	0.92	0.92	
CH_4 (a)	0.94	1.06	
NMHC (a)	0.06	0.06	
CO	0.23	0.24	
NO_x	1.09	1.46	
CO_2	387	428	
Fuel Economy, MPG	19.1	17.2	

(a) CNG Tests: Methane concentration is based on independent GC analysis. NMHC calculation from GC speciation analysis.

With respect to the average NOx emission level , the GFI system produced the lowest NOx test results for all compositions followed by the Impco and Mogas systems. The ANGI system produced even lower levels of NOx emissions with the mean and 90th percentile gas compositions, but did not pass the 1993 NOx standard of 1.0 g/mi with the 10th percentile gas composition fuel. The Impco and GFI systems passed the NOx standard while the Mogas system was slightly over the limit. In assessing these results one must take into consideration the system setup procedure. Both the Impco, and Mogas systems involved subjective tuning of the system to achieve low tailpipe emissions based on the use of a 4 gas analyzer. The subjective nature of the setup as well as the system sensitivity resulted in a lean mixture for all three of these conversion systems. This produced a combination of relatively low CO and high NOx, as would be expected. On the other hand, the GFI and ANGI systems calibrate themselves automatically, producing the opposite effect. This automatic rich setup produced surprisingly consistent low NOx values for each of the gas compositions tested, resulting in NOx emissions below both the 1993 and 1994 emission limits, except where noted above.

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